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Nonequilibrium Effects in Arc Jet Flow

SEPTEMBER 1966

Prepared by S. W. LIU and K. E. STARNER
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Laboratory Operations
AEROSPACE CORPORATION

DEC 23 1966

Prepared for BALLISTIC SYSTEMS AND SPACE SYSTEMS DIVISIONS
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

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FOREWORD

This report is published by the Aerospace Corporation, El Segundo, California, under Air Force Contract No. AF 04(695)-1001.

This report, which documents research carried out from June 1965 through August 1966, was submitted on 11 October 1966 to Captain Robert F. Jones, SSTRT, for review and approval.

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for J. G. Logan, Director
Aerodynamics and Propulsion
Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Robert F. Jones

Robert F. Jones, Captain
United States Air Force

ABSTRACT

The important features of nonequilibrium flow typical of an arc tunnel flow system are outlined. An arc heated flow system is analyzed in terms of its subsystems and corresponding local flow Damköhler numbers. Operating ranges characterized by equilibrium and frozen flow limits are specified. The effects of nonequilibrium flow on test results for a range of possible operating conditions is discussed.

NOMENCLATURE

A	Nozzle section area
C	Atom mass fraction
c_p	Specific heat at constant pressure
D	Diffusion coefficient
Dm	Damköhler numbers
h	Enthalpy
h_d	Dissociation enthalpy, $\sum C_i h_{R_i}$
h_o	Total enthalpy, $h_d + h_{sf}$
h_R	Heat of recombination
k_R	Constant portion of recombination rate coefficient
k_w	Specific catalytic surface recombination constant
l	Characteristic length $r^*/\tan \theta$
Le	Lewis number, σ/Sc
M_a	Molecular weight of atomic species
\dot{m}	Mass flow rate
P	Pressure
P_o	Total pressure
q_c	Surface convective heat transfer
q_D	Surface diffusion heat transfer
q_E	Total surface heat transfer in equilibrium flow
q_w	Total surface heat transfer

NOMENCLATURE (Cont.)

R	Body nose radius
R	Gas constant for air
R	Universal gas constant, 82.06 (cc-atm/mole-°K)
r	Nozzle section radius
S	Diffusion velocity
S	Entropy
s	Particle path
Sc	Schmidt number, ν/D
T	Absolute temperature
u	Stream velocity
Z	Compressibility factor
a	Degree of dissociation
β	External flow velocity gradient, du_e/dx
θ	Nozzle half angle
λ	Thermal conductivity
μ	Viscosity
ν	Kinematic viscosity, μ/ρ
ρ	Density
σ	Prandtl number, $\mu c_p/\lambda$
τ	Characteristic time
ϕ	Correction factor for catalytic effects

NOMENCLATURE (Concl.)

Subscripts

c	Convection
D	Atom diffusion
d	Dissociation
E	Equilibrium
e	Edge of boundary layer
f	Frozen
i	ith component of mixture
N	Nitrogen
o	Reservoir state
s	Stagnation state
w	Wall

Superscripts

*	Nozzle throat
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I. INTRODUCTION

In an arc tunnel facility, an arc heater provides high enthalpy gas for long periods for model testing. The process of arc-heating and the subsequent expansion through a nozzle, however, introduce a nonequilibrium chemical state in the gas in the test section. The accuracy with which this gas state is known often has a direct bearing on the usefulness of the arc tunnel for producing test results of quantitative significance.

Typically, an arc tunnel facility consists of: (1) an arc unit, where energy from the arc discharge is introduced into the gas; (2) a plenum chamber, where the gas mixture is allowed time to achieve homogeneity; and (3) a nozzle through which the prepared fluid from the plenum is discharged to form a well-defined test stream. The flow around the model placed in the test stream can be generally characterized by a shock layer (when the test stream is supersonic) and a boundary layer through which the fluid is brought in contact with the model surface, where a number of test measurements are made.

The chemical state of a reacting flow can be characterized by a Damköhler number Dm which is a measure of the ratio of the characteristic particle resident time to the chemical reaction time. Such Damköhler numbers can be defined for each flow region, and the ranges of each that correspond to equilibrium and frozen limits can be delineated.

This report outlines the salient features of the nonequilibrium flow typical of an arc tunnel flow system and indicates the effects of the nonequilibrium flow on the test results. Local flow states in separate subsystems are first discussed in terms of their local Damköhler numbers. The ranges of each Damköhler number that correspond to equilibrium and frozen limits are delineated. The actual determination of the flow states in a typical arc tunnel is demonstrated, and the problems of establishing proper operating conditions for testing are discussed. Other problems that arise from performance of a test and interpretation of its results are also discussed.

Since the arc tunnels are used primarily for simulating atmospheric flight conditions for materials testing, this discussion is confined to air flow systems in an arc tunnel, with stagnation point heat transfer measurement the most important test result.

II. SOURCE FLOW SYSTEM

This section examines the chemical states of air passing from the arc heater to the plenum and through the expansion nozzle to the test section. The nominal operating ranges of typical* arc units are

reservoir stagnation temperature	3,500 - 8000°K
reservoir stagnation pressure	0.05 - 10 atm
reservoir total enthalpy	3,000 - 12,000 Btu/lb

The chemical properties of equilibrium air can be accurately determined by classical thermodynamics and are available from various sources (Refs. 1 - 4). Figure 1 shows the domains of major chemical activities in equilibrium air. Curves showing the ranges of stagnation pressure and temperature of the supply gas are superimposed on these domains, indicating the chemical state of the supply gas. It is clear that dissociation of oxygen and nitrogen are the important chemical activities to consider. Energy distribution in the various degrees of freedom is given in Figure 2. In the temperature range 3000 - 8000°K, the dissociated species have high energy. Therefore dissociation and recombination kinetics and its relaxation effects play an important part in flow determination. Ionization and other excited electronic states contribute negligible internal energy in the temperature and pressure ranges of interest. For aerodynamic and heat transfer simulations these effects can be ignored.

A. PLENUM

The plenum allows the test gas to achieve mixing uniformity and assures thermochemical equilibrium before the expansion process. The detailed process is complicated and not readily describable. To provide for some gross estimate of performance we can establish an approximate criterion of

* The typical operating range listed here represents those of various test facilities currently in operation. It does not represent those of facilities under development which promise to achieve higher operating ranges.

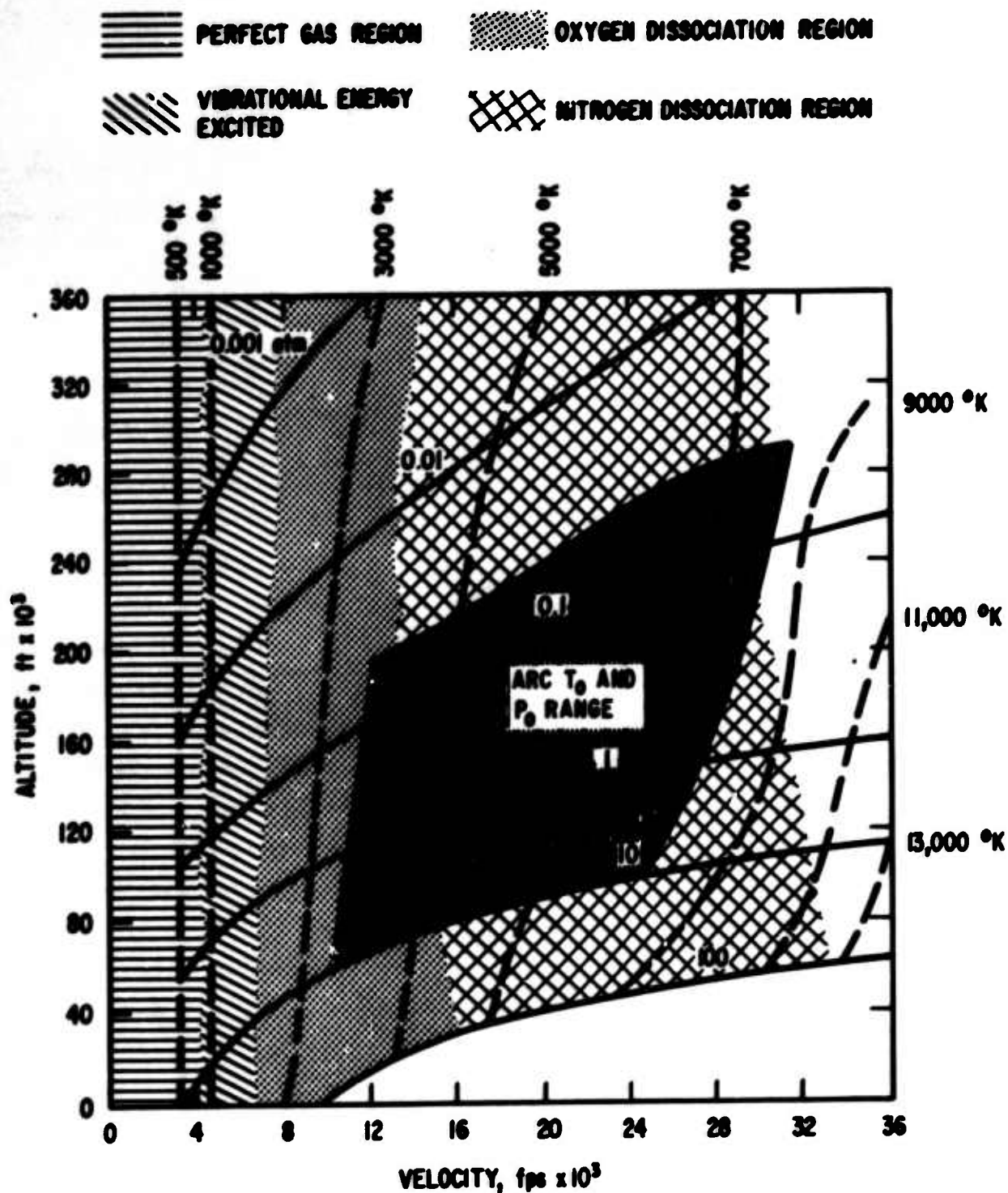


Figure 1. Domains of Major Chemical Activities of Equilibrium Air Constituents and Stagnation Temperature and Pressures Encountered as Functions of Altitude and Velocity

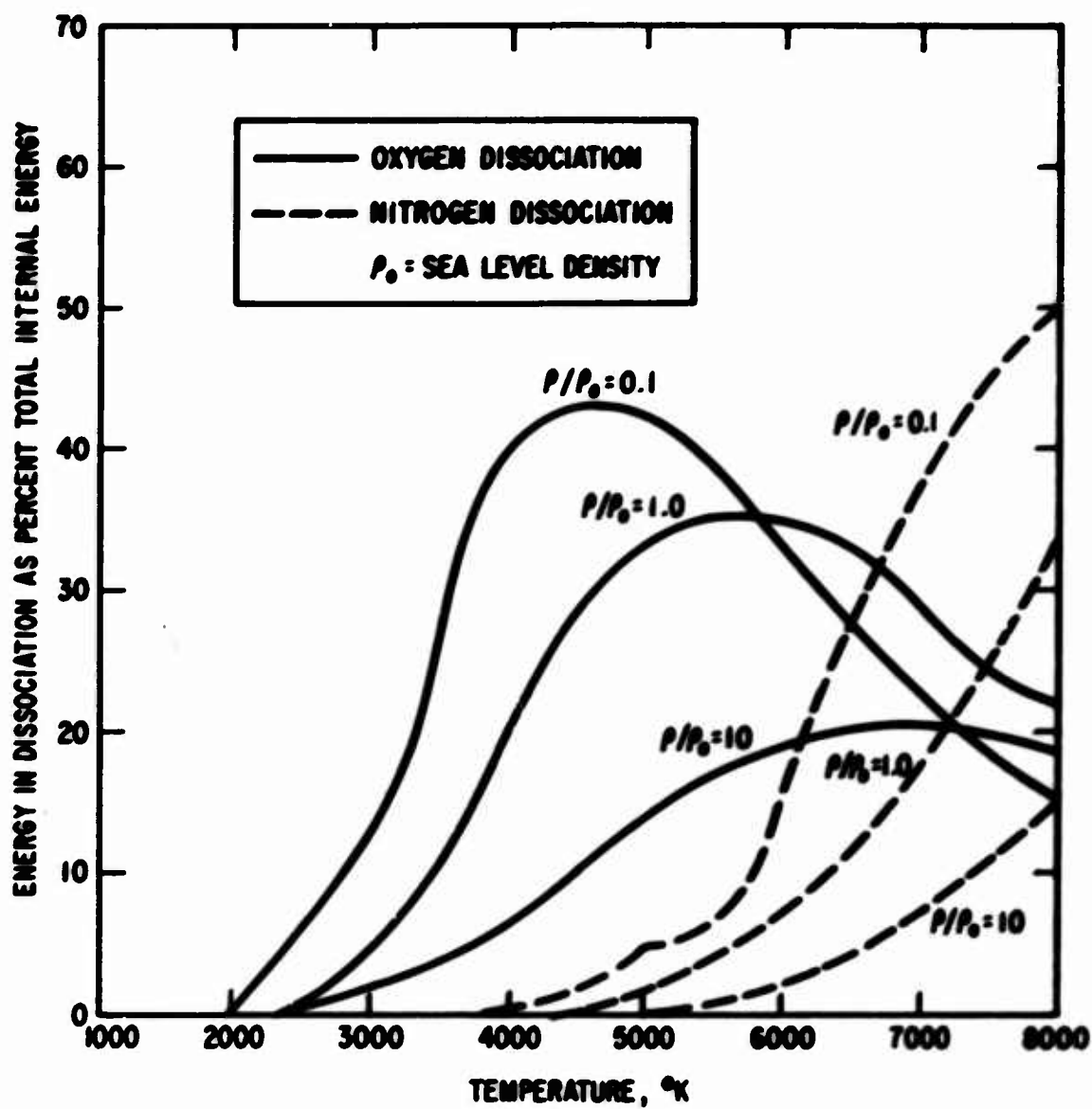


Figure 2. Energy Distribution in Dissociation

chemical time necessary for equilibrium by correlating the available results of relaxation studies of pertinent chemical processes involved (Refs. 7, 8, and 9). An upper envelope of relaxation times required for air constituents to achieve chemical equilibrium with respect to dissociation-recombination, vibration, rotation, and translation was obtained empirically based on the results of Refs. 7, 8, and 9 and is shown in Figure 3. This envelope can be compared with the estimated residence time in the plenum. When residence time falls above this envelope equilibrium state is assured. When residence time falls below the envelope some modes of nonequilibrium may exist. Since the state of the art of chemical kinetics of air constituents is such that many uncertainties still exist, the criteria set forth above can be regarded as only a rough guide, to be corroborated whenever possible by actual measurements of gas states. A Damköhler number for the plenum can be constructed

$$Dm_1 = \frac{(P\tau)_{\text{envelope}}}{P \int_s \frac{1}{u} ds} \quad (1)$$

where residence time is expressed as the reciprocal of particle velocity, u , integrated over the particle path, s . The chemical state of the gas is indicated by the following limits:

$$Dm_1 \leq 1 \quad \text{equilibrium}$$

$$Dm_1 \gg 1 \quad \text{nonequilibrium}$$

The correlation is such that only the equilibrium limit is comparatively well defined.

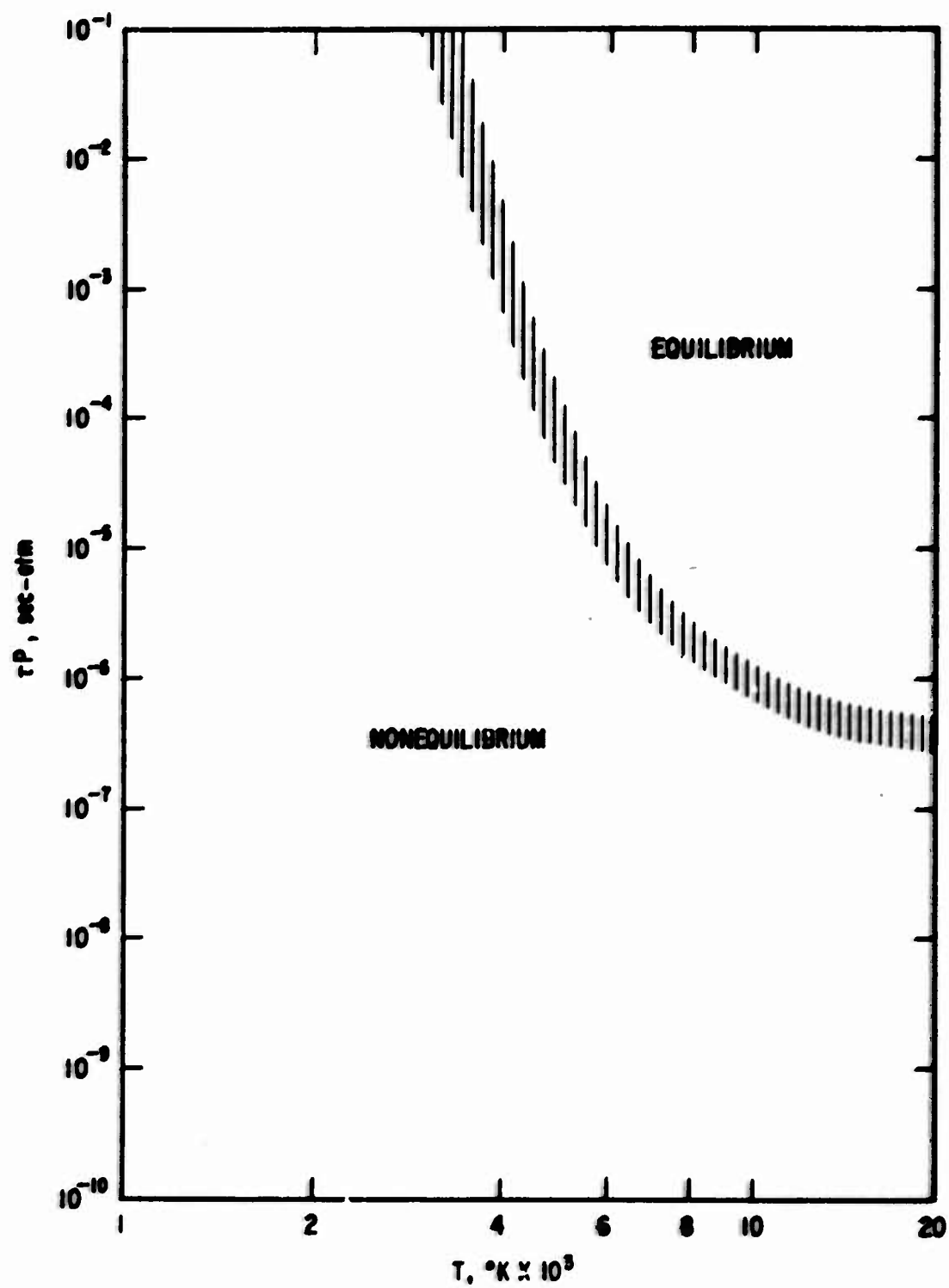


Figure 3. Approximation Correlation of Gas States of Air in a Plenum

B. NOZZLE FLOW

It is now assumed that the gas reaches thermochemical equilibrium in the plenum before expansion through the nozzle proceeds. The rapid acceleration of flow in the nozzle causes high rates of change in the thermodynamic state of the gas. The ability of the chemical state to keep pace, therefore, depends on the relaxation time of the pertinent chemical processes under local flow conditions. In general, the nozzle flow equations must be solved simultaneously with chemical rate equations to obtain an accurate account of the flow variables. A number of machine computing programs are now available. The solutions are exact in the sense that the accuracy of these results is limited only by the correctness of chemical reaction rates assumed and by simplifying assumptions that are used in describing the nozzle flow.

For complete simulation of actual atmospheric flight conditions, it is obviously desirable to maintain equilibrium expansion through the nozzle into the test section. In most shock tunnel applications, efforts have been directed toward operations under equilibrium flow conditions. This generally requires a high reservoir pressure and a relatively low reservoir temperature. When such conditions are not readily obtainable due to operational limitations of test facilities, the use of nonequilibrium test streams must be considered. Many meaningful test results can be obtained under such conditions, provided that the nonequilibrium flow states can be correctly identified.

In high enthalpy arc tunnels, the reservoir pressure level is limited by arc-head heat transfer limitations or available electrical power, so that nonequilibrium nozzle flow is a primary mode of operation.

In the frozen limit of a nonequilibrium flow, the chemical states of the gas are fixed and the determination of flow is therefore greatly simplified, provided that the onset of the frozen states can be correctly specified. Two simplified methods by which practical calculation of frozen flow in a nozzle can be made without elaborate machine computation are discussed below.

1. SUDDEN FREEZING SCHEME

Consider a diatomic gas wherein dissociation-recombination kinetics is the governing mechanism which affects the departure from equilibrium. An analysis was first made, with particular reference to nozzle flow, by Bray (Ref. 9), using the ideal dissociating gas model of Lighthill (Refs. 10 and 11). By combining the one-dimensional nozzle flow equation and the chemical kinetic relationships, we can identify a Damköhler number for the flow, which is expressed in terms of local equilibrium thermodynamic and flow variables. When the Damköhler number is larger than a certain value the flow can be considered in equilibrium. On the other hand, when the Damköhler number drops below a certain value chemical kinetic activities effectively cease and the chemical constituents of the gas remain constant (i. e., "frozen"). In a nozzle flow, the change in Damköhler number is drastic enough that its numerical value, corresponding to where the sudden freezing occurs, can be closely bracketed, giving a sudden freezing criterion. A useful simplified scheme for nozzle flow solutions has been devised based on such criteria. A discrete numerical value of the sudden freezing Damköhler number was obtained by Bray from correlation of the result of exact solutions (Ref. 9). This simplified method is especially useful when knowledge of the ultimate chemical state of the gas, but not of its intermediate stages, is of importance, such as in most test facility applications. The calculation is carried out by assuming equilibrium flow conditions until the local Damköhler number reaches the sudden freezing value. Beyond this point calculation proceeds using frozen flow conditions.

Exact calculations of high enthalpy air flow through a nozzle of a hypersonic shock tunnel have been obtained by the CAL group (Refs. 12, 13, and 14). In the temperature range where dissociation-recombination kinetics is predominant ($T < 8000^\circ\text{K}$), air behaves very much like a pure diatomic gas and can be treated as such (Ref. 15). Sudden freezing criteria, which Bray developed for a diatomic gas, have also been established for oxygen atom recombination in air (Ref. 12); these correlated successfully with the exact calculations of CAL.

The freezing criterion makes it practical to obtain results with a desk calculator. For example, Pearce et al. (Ref. 5) construct a map of estimated frozen atom mass fraction in terms of reservoir states of air for a specific nozzle ($1.0 < P_0 < 1000$; $4000 < T_0 < 16,000^\circ\text{K}$; $r^* = 0.05\text{ cm}$; $\theta = 7.5\text{ deg}$) using an oxygen recombination rate law. This map summarizes the general trend of nonequilibrium nozzle flow and makes it convenient to fix the reservoir temperature and pressure under which nonequilibrium effects are confined to tolerable limits. While the overall trend is of general interest, the specific results are not directly applicable to the arc tunnel of present consideration because of differences in pressure range and nozzle geometry. The sudden freezing criterion is, in essence, an empirical scheme based on correlation of known exact results; extrapolation to other ranges of gas states and nozzle geometries must therefore be considered tentative until further checks can be made by exact results in the corresponding ranges of gas states and nozzle configurations. The Aerospace nozzle flow computing program is currently being adapted to obtain solutions directly appropriate to the conditions of the arc facilities under development in this laboratory.

2. FREEZING POINT ENTHALPY CORRELATION

Another simple method of predicting the freezing level of dissociating atom mass fraction due to oxygen atoms in air is outlined below. Bray (Ref. 16) has made further study of the freezing criterion and noted, from his ideal gas model with a single chemical reaction, that the gas enthalpy at sudden freezing is nearly a function of only the reservoir entropy. From the results of previous calculations, he has constructed on a Mollier chart a single curve on which the freezing states for all reservoir conditions appear to coalesce. The same approach was extended by Bray to the air expansion results of Hall (Ref. 12) for a predominantly oxygen atom region ($T_0 = 5000$ and 6000°K and $P_0 = 100$ and 1000 atm), and a mean freezing curve, which has the general features of the ideal gas case, was obtained. In Figure 4 two freezing curves, drawn on a standard Mollier chart, correspond to normalized throat dimensions bracketing the nozzle dimension range of our

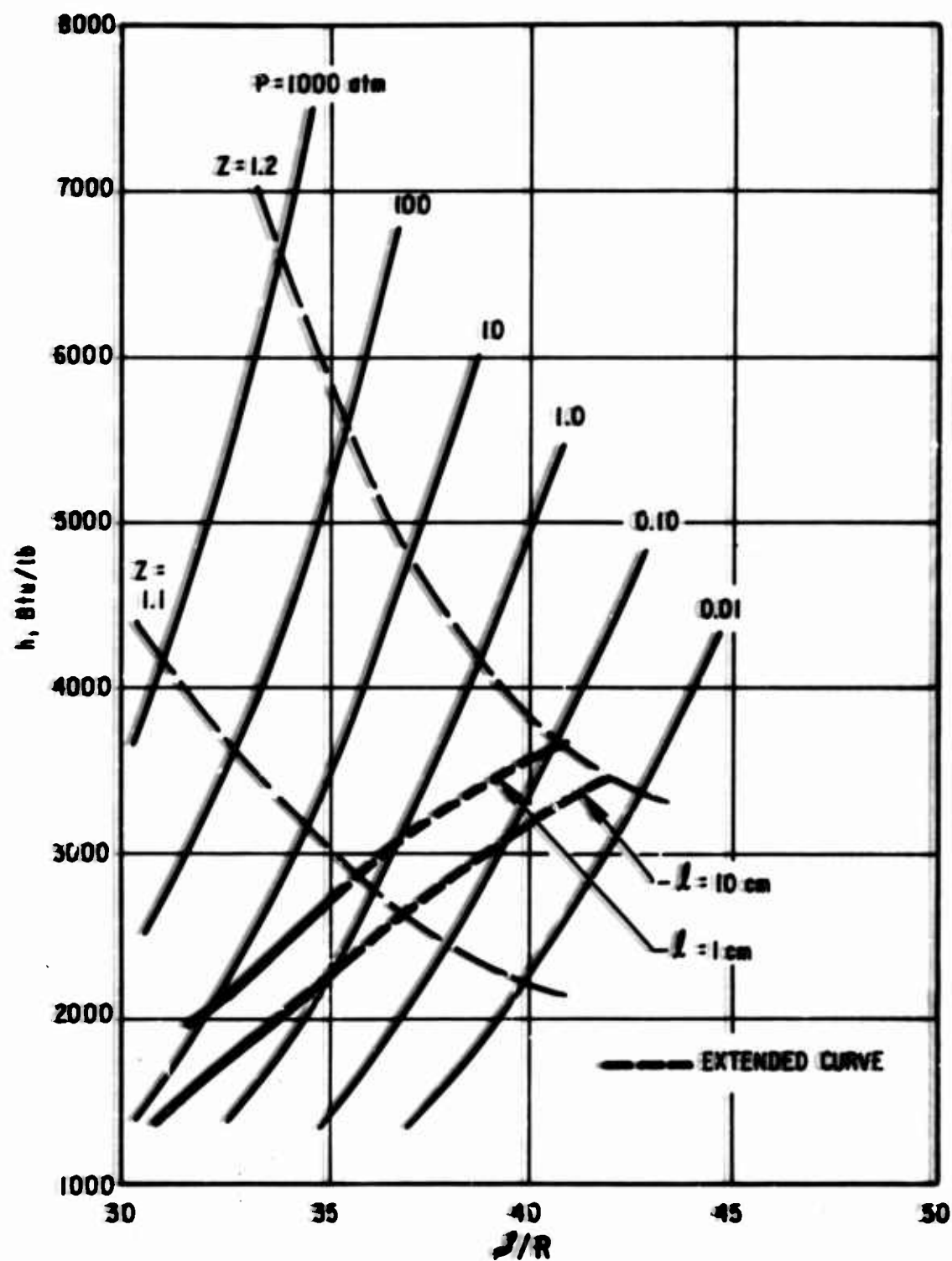


Figure 4. Sudden Freezing Criteria Shown on a Mollier Chart for Air

interest. These curves are based on the results of Ref. 16 and are extended to the region of present interest. A few cases of nozzle calculation by sudden freezing criteria using arc tunnel operating conditions correlate with the extended freezing curve to about 10 percent. Since the dependence on the l parameter is linear (Ref. 16), results for values of l between 1 and 10 cm can be obtained by interpolation. To obtain the gas freezing state, one needs only to locate the stagnation state on the chart and drop down a vertical (isentropes) until it meets the freezing curve. The intersection gives the freezing state. The frozen flow downstream of the freezing line is not given on this chart. For a given fixed freezing curve we can alter the downstream portion of the Mollier chart so that it is appropriate for a frozen isentropic flow (Ref. 5); this forms a combined Mollier - frozen flow chart for use in a specific nozzle (Ref. 16). Because the results of Refs. 12 and 16 apply only for the case of oxygen dissociation-recombination kinetics, the plenum (starting) conditions of Figure 4 are limited to maximum Z values in the range of 1.2, below which nitrogen dissociation is negligible.

Williams (Ref. 18) derives a sudden freezing enthalpy Damköhler number Dm_2 for nozzle flow for use in a region where oxygen dissociation-recombination reactions play the major role in air kinetics. This is consistent with the discussion in the preceding paragraph, and the same limitations apply. From Ref. 18

$$Dm_2 = \frac{k_R \rho^*{}^2 r^* R^2}{M_a^2 h^{5/2} \theta} \quad (2)$$

where the oxygen recombination rate coefficient is equal to $k_R (3000/T)^2$ with $k_R = 1.16(10)^{15} \text{ cm}^6 \cdot \text{K}^2/\text{mole}^2\text{-sec}$. Figure 5 shows that the enthalpy at sudden freezing is largely dependent upon Dm_2 and is less sensitive to stagnation temperature. This Damköhler number is a function of easily determined plenum and throat conditions and does not involve the detailed local expansion calculations referred to in Section B1.

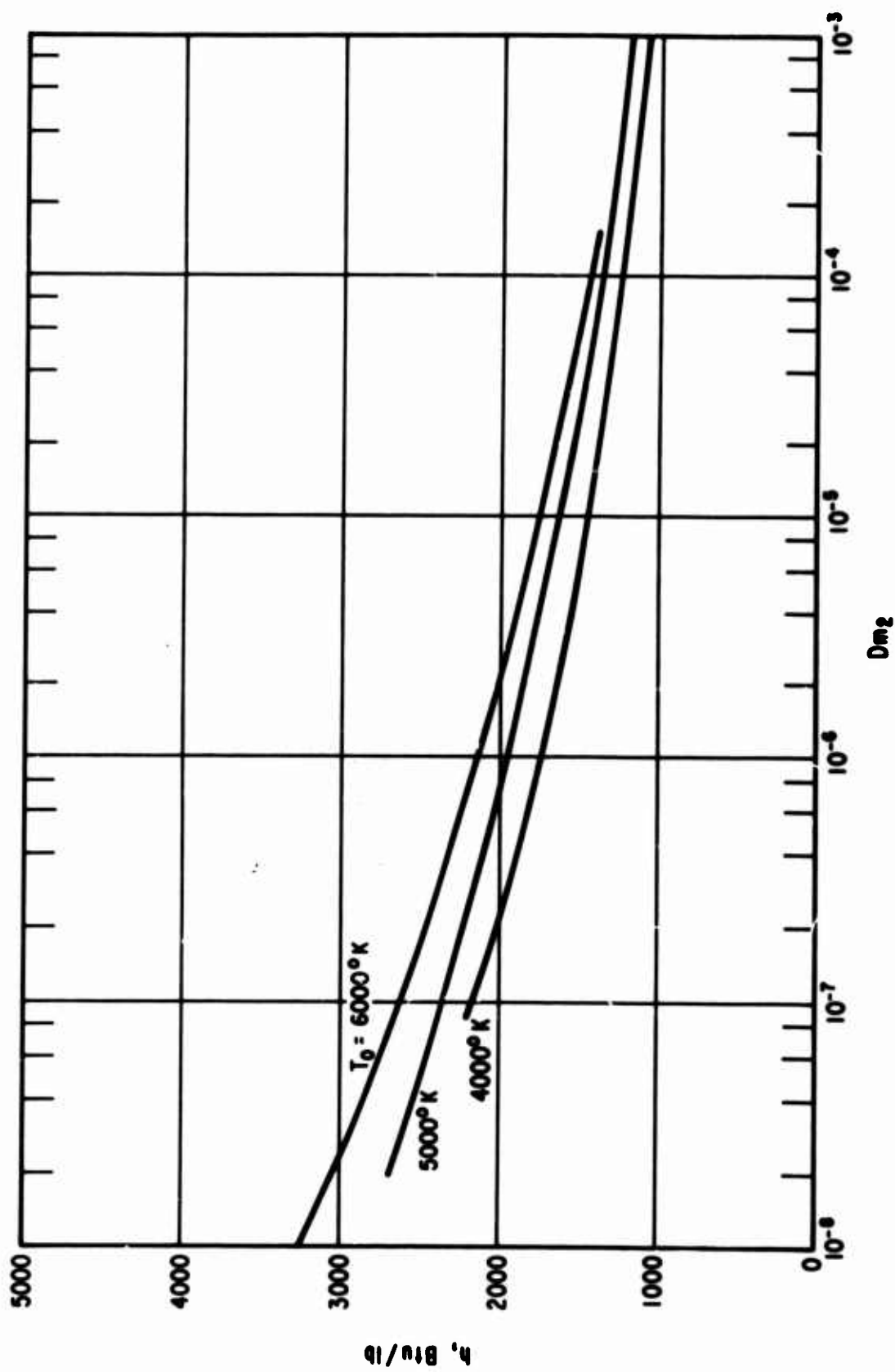


Figure 5. Sudden Freezing Enthalpy as a Function of Dm_2 and Plenum Temperature

Lordi and Mates (Ref. 19) discuss calculations of chemical nonequilibrium expansions of six neutral species, N_2 , O_2 , NO, N, O, and Ar, which are vibrationally and electronically excited and undergo coupled chemical reactions. They point out that the sudden freezing approximation is not usually accurate for flows with coupled reactions, but that it is possible to correlate the exit frozen enthalpy with plenum entropy for several cases, including those of Ref. 14, as shown in Figure 6. This correlation from Ref. 19 does not give a sudden freezing point, but rather tells the value of enthalpy frozen in the expansion at the exit of large area-ratio nozzles at a given plenum entropy. Figure 6 is used to locate plenum conditions and frozen exit enthalpy only and cannot be used to trace the expansion process. Theoretical cases correlated within 10 percent in the construction of Figure 6 involved pressures from ten to several thousand atm and temperatures from 8000 to 15,000°K. As is shown in Section IV, the value of dissociation enthalpy frozen into the flow is of major importance in predicting heat transfer rates to bodies placed in the flow.

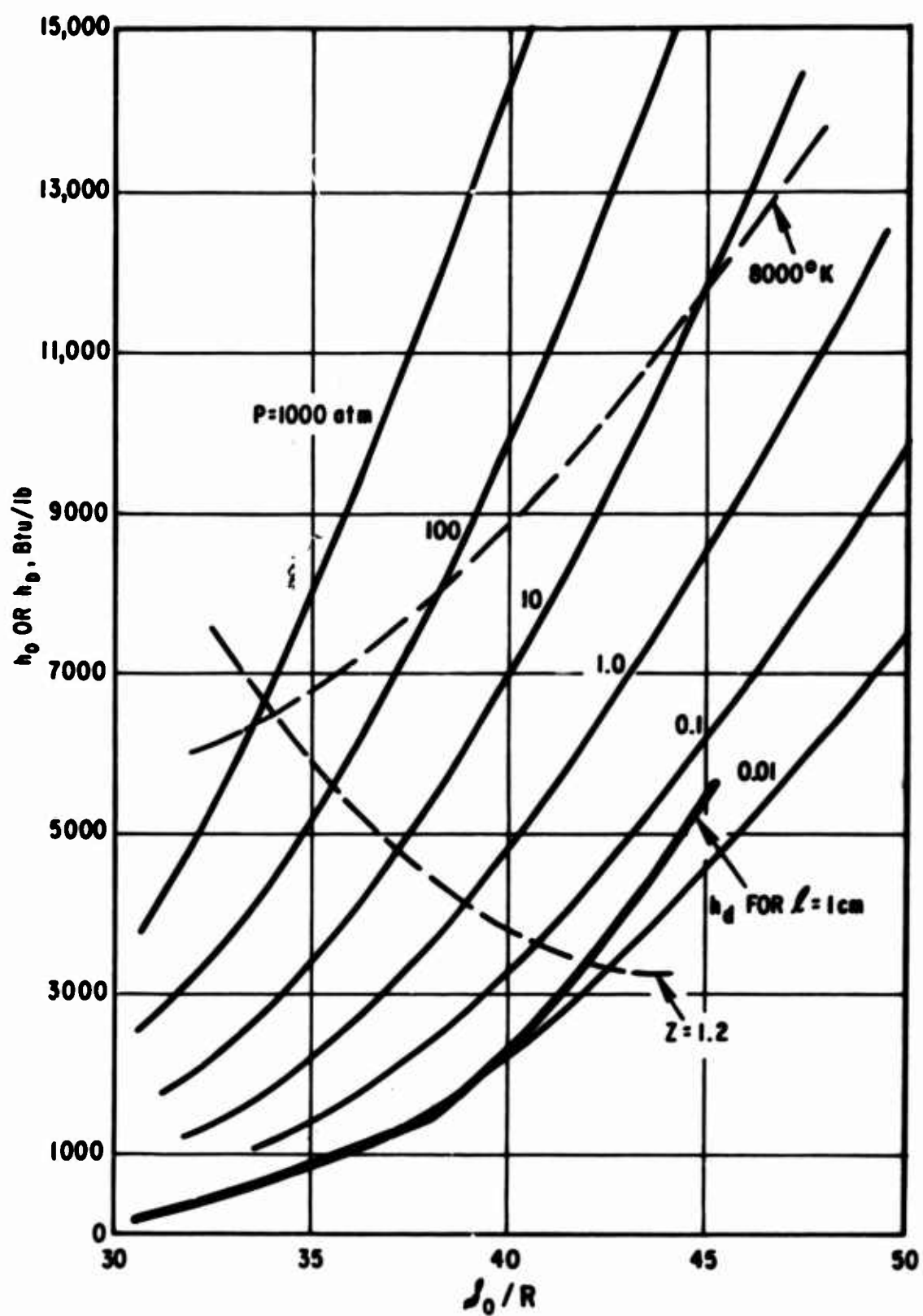


Figure 6. Frozen Enthalpy at Nozzle Exit Shown on a Mollier Chart for Air

III. FLOW NEAR THE BODY

This section examines the chemical states of the flow about a test model placed in a supersonic test stream provided by the nozzle. It is assumed that the Reynolds number of the nozzle flow in the test section is high enough that continuum flow with distinct shock layer and boundary layer exist in the neighborhood of a body ($Re = \rho_{\infty} u_{\infty} R / \mu_s \gg 25$). Although in the lower range of the Reynolds number some solutions for viscous shock layers are also presently available, they are much less definitive in their interpretation and will not be included in this discussion. For quantitative evaluation of test results, it is highly desirable to operate under conditions where the flow is well within one limiting flow regime or the other (equilibrium or frozen). This is true for nozzle flow, as well as for shock layer, boundary layer flows, and surface reactions. In the following, the flow regimes (equilibrium-frozen) of shock layer, boundary layer and surface are outlined separately and their effects in the determination of test results are noted.

At present, arc tunnel operations are chiefly geared to delivering known heat flux to models. In the following discussion, the effect on stagnation point heat transfer will be considered.

A. SHOCK LAYER

Detailed numerical results of a shock layer flow in front of a blunt body have been given in Ref. 20. The chemical state of the air flow in the shock layer can be correlated from these results by a Damköhler number. Several similar versions of the Damköhler number for air have been reported (Refs. 21 and 22). The one given below, which is considered most current, is from Ref. 22.

$$Dm_3 = (8.6 \times 10^{16}) \left(\frac{2R}{u_{\infty}} \right) \left(\frac{P_s}{4R^2 T_{sf}^{3.5}} \right) \exp(15.8 - 60,000/T_{sf}) \quad (3)$$

where

R = body nose radius, ft

u_{∞} = free stream velocity, ft/sec

P_s = model stagnation pressure, atm

T_{sf} = frozen stagnation temperature, °K

R = universal gas constant, 82.06 cc-atm/mole °K

The practical range of limiting flow regimes has been indicated as

$Dm_3 < 10^{-2}$ frozen shock layer

$Dm_3 > 10$ equilibrium shock layer

Among flow quantities required for the determination of heat transfer at the stagnation point (see Section B) all, except those depending on surface conditions, can be determined from shock layer analyses. For either frozen or equilibrium flows, they are readily available (Refs. 15, 23, and 24). It has been shown that flow properties in the shock layer are not sensitive to the dissociation nonequilibrium state of the flow. The dissociation level of the gas, however, needs to be accurately determined, since heat transfer due to surface recombination in a frozen boundary layer is directly proportional to the energy carried by atoms.

B. BOUNDARY LAYER

Similar correlations of chemical states of air in terms of Damköhler numbers also exist for the boundary layer flows (Refs. 15, 22, 25, 26, 27 and 28). A comprehensive correlation derived from the results of Refs. 15, 25, and 26 is given in Ref. 27. Such results are for noncatalytic surface conditions. For the purpose of defining flow regimes (equilibrium or frozen), the correlation is valid without regard to the surface catalytic activities. The actual heat transfer values, of course, are to be determined in conjunction

with the surface Damköhler number to be discussed in Section IV. The boundary layer flow Damköhler number, from Ref. 27 is:

$$Dm_4 = \left[\frac{1}{\beta} (3.12 \times 10^{20}) \frac{1}{T_{se}^{3.5}} \left(\frac{P_s}{R} \right)^2 \right] \left[\frac{h_R}{h_{fs}} \left(\frac{C_e}{1+C_e} \right) \left(\frac{1}{1-C_{Ne}^2} \right) \right] \left(\frac{1500}{T_w} \right)^{3.5} \quad (4)$$

where

$$\beta = \frac{u_\infty}{R} \left[\frac{\rho_\infty}{\rho_{es}} \left(2 - \frac{\rho_\infty}{\rho_{es}} \right) \right]^{1/2} \quad (\text{sec}^{-1}) \quad (\text{using hypersonic approx.})$$

T_{se} = stagnation temperature outside boundary layer, °K

\bar{h}_R = average heat of recombination, $\sum C_i h_{R_i} / \sum C_i$

h_{sf} = frozen stagnation enthalpy, $\int_0^{T_e} \bar{c}_p dT + u_e^2/2$

c_e = mass fraction of air atoms outside boundary layer

C_{Ne} = mass fraction of nitrogen atoms outside boundary layer

T_w = wall temperature, °K

The practical range of limiting flow regions is

$$\begin{array}{ll} Dm_4 < 10^{-3} & \text{frozen boundary layer} \\ Dm_4 > 10^2 & \text{equilibrium boundary layer} \end{array}$$

IV. SURFACE CATALYTIC REACTION AND HEAT TRANSFER

In this section the heat transfer to the model of catalytic surfaces in a dissociated stream is considered. In the temperature range of arc jet flow, the energy carried by the atoms in dissociated states is sizable. The amount of dissociation energy released to the surface, in turn, depends on the atom diffusion flux and the catalytic efficiency of the surface to promote recombination. The expression for heat transfer to a body in a dissociated stream is first given as

$$q_w = q_c + q_D \quad (5)$$

The total heat flux to the wall, q_w , is made up of contribution by molecular convection, q_c , and that by atom diffusion, q_D . Expressions for q_c and q_D from known results for cooled wall blunt body stagnation point with frozen boundary layer are (Refs. 15, 23, and 24).

$$q_c = (0.47)(2\beta\mu_{es}p_{es})^{1/2} \bar{\sigma}_w^{-2/3} h_{sf} (\bar{h}_w \ll h_o) \quad (6)$$

$$q_D = (0.47)(2\beta\mu_{es}p_{es})^{1/2} Sc^{-2/3} h_d \phi$$

where

$$\phi = \left[1 + \frac{S}{k_w} \right]^{-1}, \quad 0 < \phi < 1 \quad \left(0 < \frac{k_w}{S} < \infty \right)$$

$$S = (0.47)(2\beta\mu_{es}p_{es})^{1/2} Sc^{-2/3} p_w^{-1}$$

k_w = specific surface catalytic recombination coefficient

$$h_d = \sum C_i h_{R_i}, \quad \bar{\sigma} = \frac{\mu \bar{c}_p}{\lambda}, \quad Sc = \frac{\mu}{\rho D}$$

The factor ϕ is derived from the simultaneous solutions of momentum and species equations in a frozen boundary layer flow of dissociated gases with catalytic surface recombination (Ref. 24). It can be considered a surface catalycity parameter whose limiting values correspond to that of the surface catalytic activities in terms of k_w , as noted in the above expression. Consistent with the above discussion, the net effect of surface catalytic reaction on heat transfer can also be discussed in terms of a surface Damköhler number, which is related to ϕ as follows:

$$Dm_5 = \frac{k_w}{S} = \frac{\phi}{1 - \phi} \quad (0 < Dm_5 < \infty) \quad (7)$$

As noted in the general discussion of Damköhler number outlined in the Introduction, surface catalycity alone is not sufficient to establish a criterion. The overall effect depends as well on the flow characteristics in terms of quantities in the expression of S , the characteristic diffusion velocity across the boundary layer. The range of Dm_5 attainable in practical conditions has been discussed in Refs. 22 and 24. The specific surface catalytic reaction coefficient k_w is a material property which, for each surface material, depends on the gaseous reactant and surface temperature. Some typical values, obtained experimentally, are available in Ref. 24.

A few approximate analyses of nonequilibrium boundary layers with arbitrary surface catalytic activities are available (Refs. 29 and 30). They are useful in assessing the relative effects of the boundary layer nonequilibrium and the surface catalytic activity when the limiting conditions (equilibrium or frozen boundary layer, fully catalytic or non-catalytic surface) are not achieved because of the limitations imposed either by the test facility or the choice of surface material. Results of Ref. 29 are given here as Figure 7. Values of $q_w - q_c / q_E - q_c$ are presented in terms of Dm_4 and Dm_5 where q_w is the actual total heat transfer to the cooled blunt body stagnation point and

$$q_E = 0.47(2\beta\mu\rho)^{1/2}\sigma^{-2/3}(h_o) \quad (8)$$

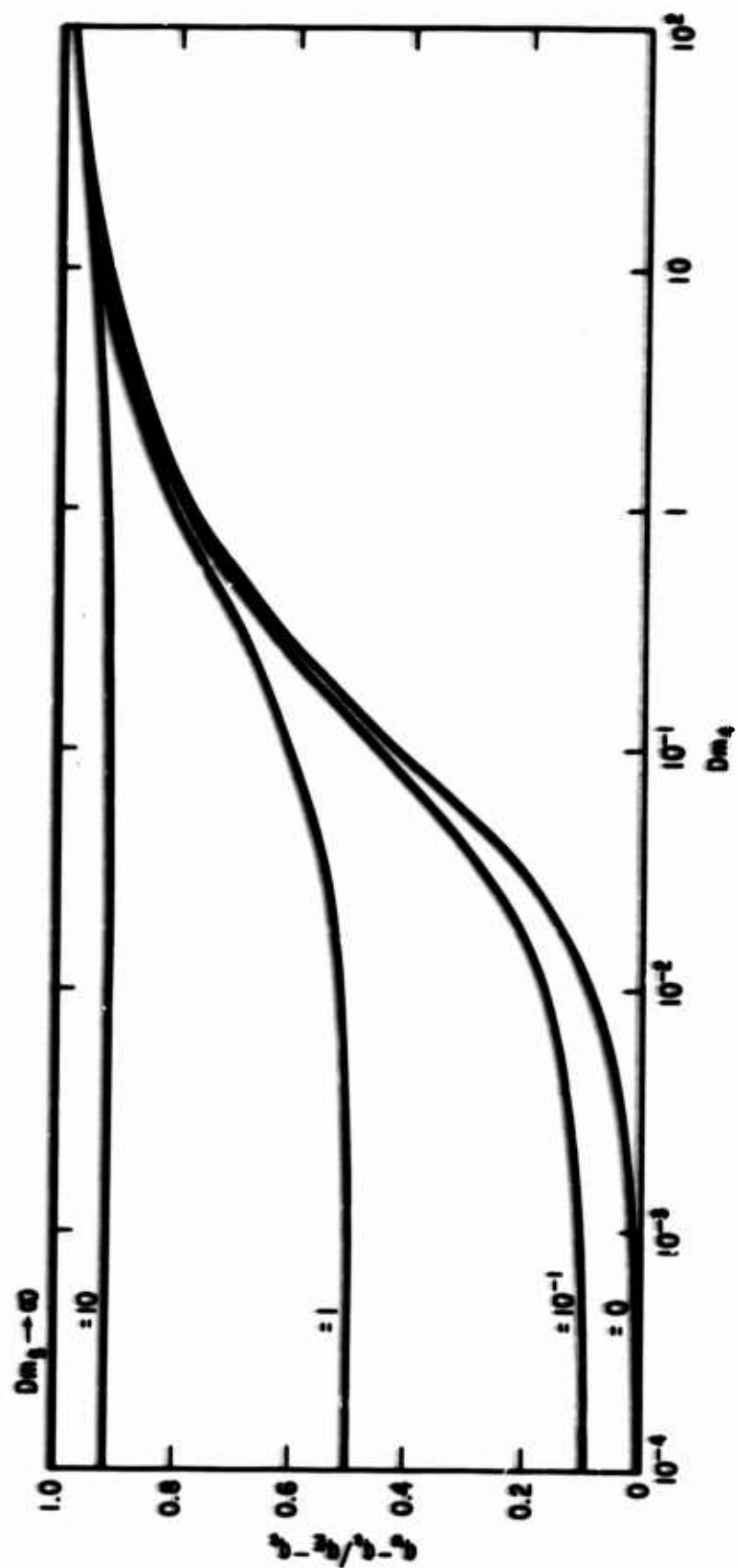


Figure 7. Variation of $(q_w - q_c) / (q_E - q_c)$ with Respect to Dm_4 and Dm_5

is the heat transfer for equilibrium flow. The boundary layer correlation for frozen flow ($D_4 < 10^{-4}$) is included in Figure 7, and by use of Eqs. (5) and (6) can be shown to be

$$\frac{q_w - q_c}{q_E - q_c} = \phi Le^{2/3} \quad (9)$$

V. DETERMINATION OF FLOW STATES IN A TYPICAL ARC TUNNEL AND EXPERIMENTAL CONSIDERATIONS

Arc tunnel flows are often required to operate under nonequilibrium states in some part of the flow system. Correct determination of the flow in each of the subsystems, as outlined above, is therefore essential for meaningful interpretation of the test results obtained. The typical operating mode of an arc tunnel entails an equilibrium plenum and a frozen nozzle flow. Options are open in principle for the flow about the model. The shock layer and boundary layer each can be separately in equilibrium or frozen states. But in practice, the prevailing flow conditions are such that, in most instances, both shock layer and boundary layer are likely to exist in equilibrium or frozen states concurrently. In the equilibrium case, the fluid state is determinate without regard to the flow history prior to its passage to the shock layer. If at the same time the surface temperature is sufficiently low, surface catalytic activity is also irrelevant to the result of heat transfer, since equilibrium atom concentration is insignificantly low at low temperatures, so that few atoms will reach the surface before recombining in the boundary layer. In the frozen case, however, the energy carried by the dissociated species is delivered directly to the surface and released through catalytic recombination at the surface. Although the differences in fluid properties as a result of differences in flow states are considered of minor importance, the surface catalytic activity plays a significant role in the determination of surface heat transfer.

In Sections A through D, criteria discussed above are used to determine the representative operating conditions that exist in the 200-kw supersonic arc facility presently in use in this laboratory. Experimental considerations regarding heat transfer measurements under such conditions are also discussed.

A. PLENUM GAS CONDITION

The following nominal reservoir condition is chosen for an illustrative example:

$$P_0 = 0.209 \text{ atm}$$

$$T_0 = 5,800^\circ\text{K}$$

The reservoir density is estimated from equilibrium conditions to be

$$\rho_0 = 5.80 (10)^{-4} \text{ lb/ft}^3$$

The velocity is estimated from the measured mass flow rate and the sonic throat conditions. A conservative estimate of residence time in the plenum is made by taking the velocity as given by the one dimensional flow through the plenum in the axial direction. Without making allowance for mixing, which undoubtedly is taking place, this represents the shortest mean particle path for the flow. The measured mass flow rate is 1.86 g/sec, from which resident time is estimated as about 300 μsec , which gives $(P\tau)_{\text{resident}} \approx 0.6 \times 10^{-4}$. This point lies above the envelope of Figure 3, indicating that equilibrium is achieved in the plenum. At lower reservoir pressure and temperature, conditions are increasingly marginal. Since it is difficult to obtain sensible estimates of resident times under actual plenum flow conditions, development of some experimental sensor may be desirable to provide for a more direct method of obtaining the information required.

B. NOZZLE FLOW

Calculations based on the sudden freezing scheme outlined above indicate that, under the operating range of the nozzle in this laboratory freezing occurs in most instances very near the sonic nozzle throat. Therefore a substantial amount of energy is carried by the frozen species. The magnitude of this problem is illustrated for a supersonic nozzle in Figure 8.

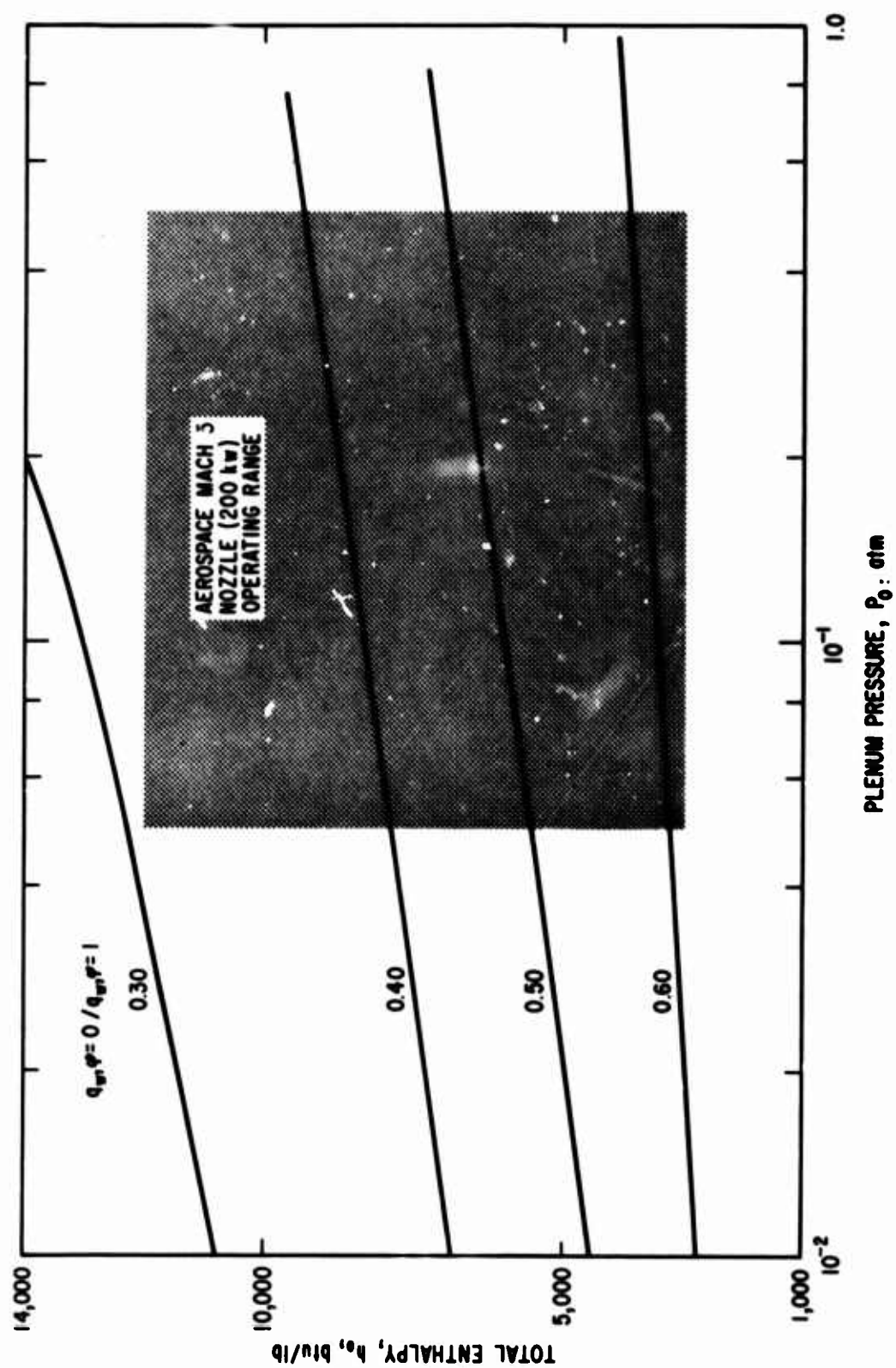


Figure 8. Heat Flux to Fully Catalytic and Noncatalytic Models for a Range of Plenum Enthalpy and Pressure

The chemical reactions are assumed to freeze at the throat and $Le = 1$. It is seen that for models having the maximum spread of effective catalytic efficiency ($\varphi = 0$ to $\varphi = 1$) large differences in heat transfer are possible. A model with $\varphi = 1$ would be expected to receive over 3 times the heat flux to a $\varphi = 0$ model at the highest enthalpy illustrated.

C. SHOCK LAYER AND BOUNDARY LAYER

The chemical states of shock layer and boundary layer are near enough that their operating conditions are governed by nearly the same ranges of flow parameters. Only boundary layer calculations are given here. Figure 9 shows approximate values of the boundary layer flow Damköhler number Dm_4 for a $M = 5$ flow over hemispherical models for a range of plenum enthalpy and pressure. Even for the maximum plenum pressure of 0.5 atm, as found with the 200-kw, $M = 5$ arc in this laboratory, little gas phase recombination can be expected for models in the range of 1-in. radius, as Dm_4 much above 10^{-2} is not possible (see Figure 7). As $Dm_4 \sim R$, it is clear that probes of a smaller radius could only decrease Dm_4 to give more assurance of freezing. On the other hand, much larger probes are limited by nozzle exit diameter, so that the conditions of frozen shock and boundary layers are rigidly fixed for this particular arc tunnel.

D. SURFACE CATALYCITY AND HEAT TRANSFER

The plot shown in Figure 10 is convenient for estimating possible heat transfer differences over the range of φ and (h_d/h_o) expected in any facility. This plot illustrates the total heat transfer to a model assuming no gas phase recombination. Figure 10 incorporates the simplifying assumption that $Le = 1$ in Eqs. (5) and (6), which can be shown to give

$$q_w/q_E = 1 + (\varphi - 1) \frac{h_d}{h_o} \quad (10)$$

It is of interest to compute limiting values of φ for the Mach 5 arc tunnel in this laboratory. Values of k_w quoted in the literature range from 1.0 cm/sec

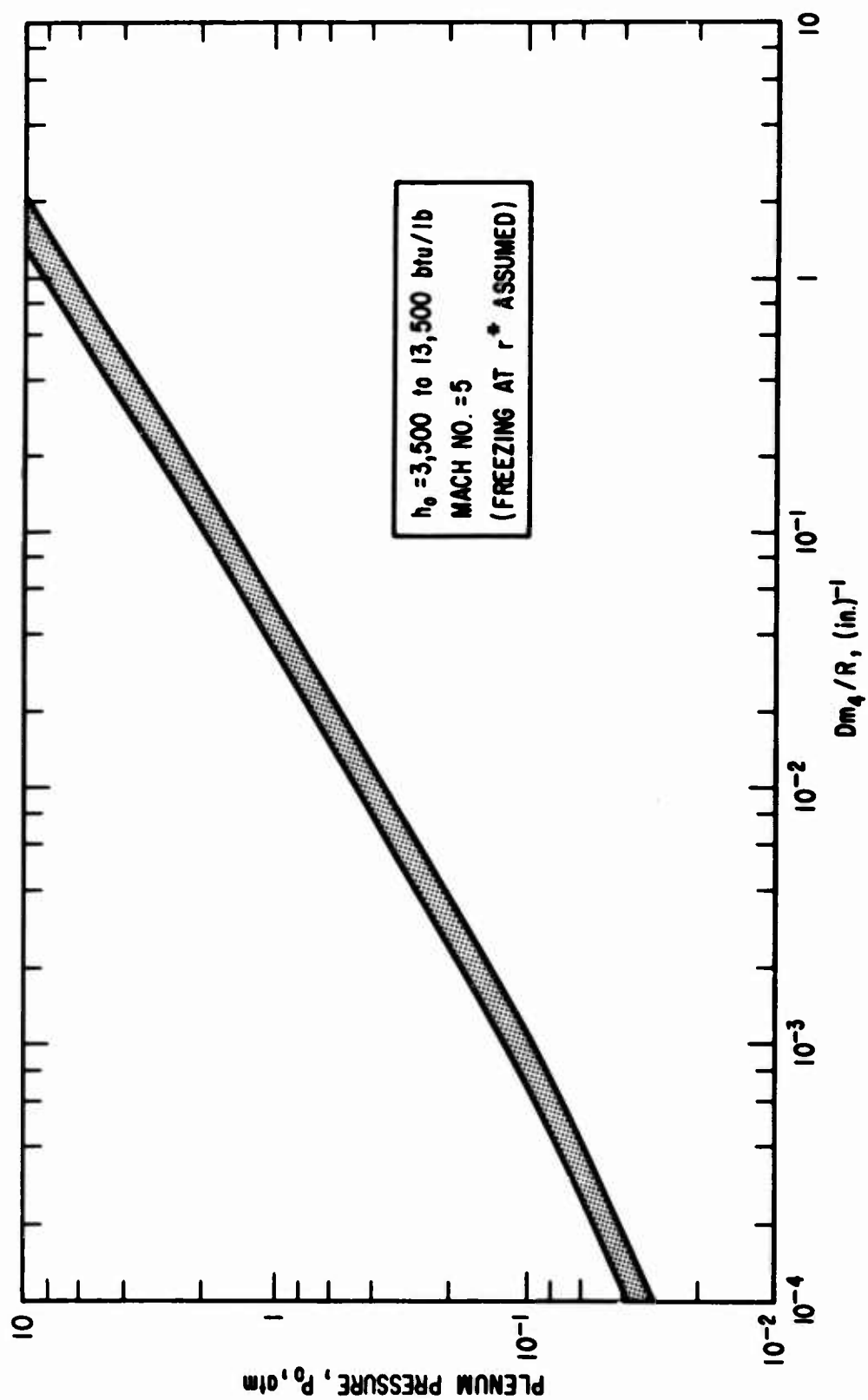


Figure 9. Boundary Layer Damköhler Number for a Range of Plenum Enthalpy and Pressure

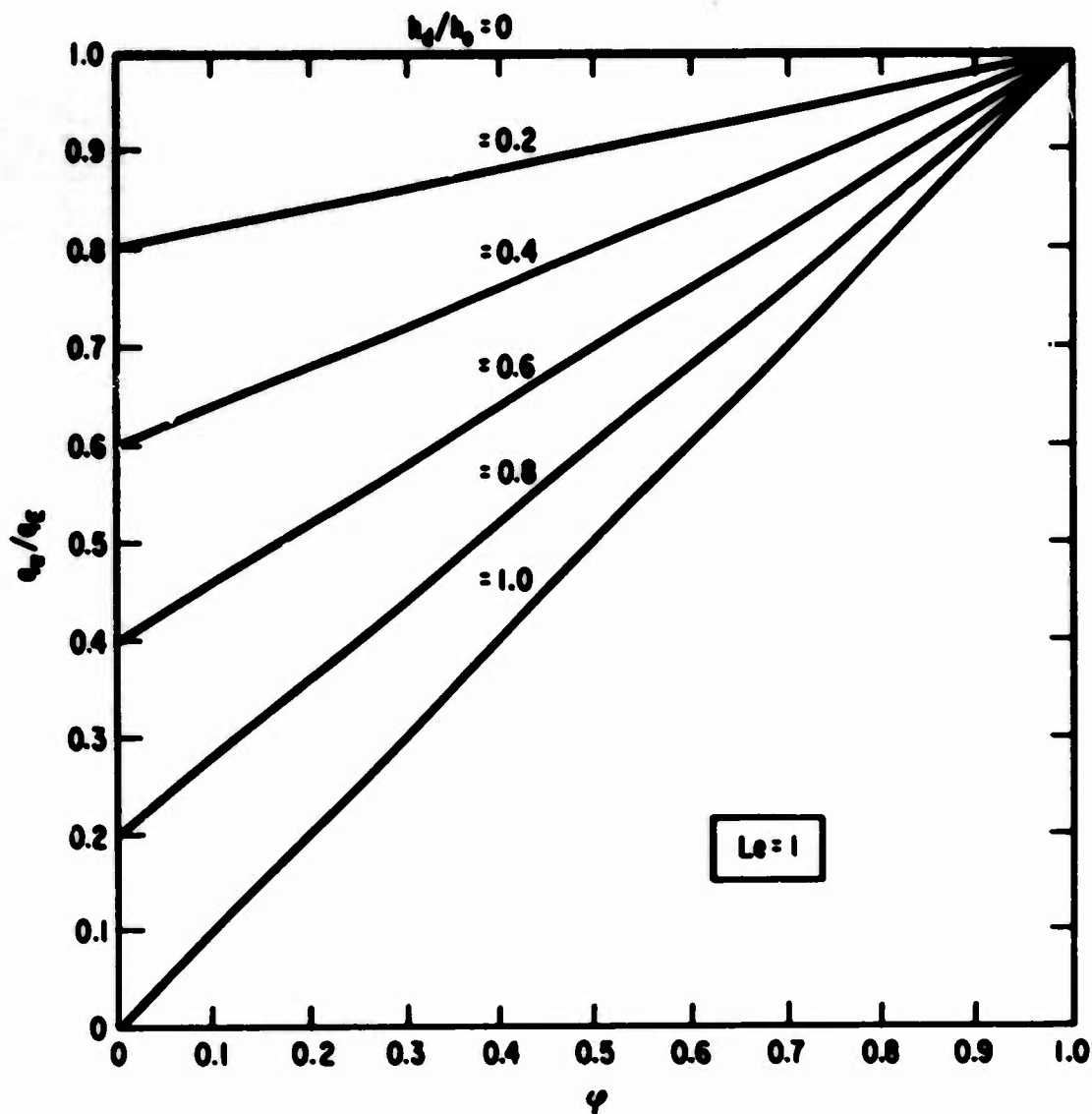


Figure 10. Heat Flux Ratio as a Function of h_d/h_0 and ϕ

for noncatalytic surfaces to over 10^4 cm/sec for the best catalyst. Very small-diameter hemispherical probes ($R \approx 0.01$ in.) would yield values of S in the range of 6×10^3 cm/sec maximum, while minimum S values for usable large, flat-faced models ($R \approx 1.0$ in.) would be near 3×10^2 . Thus, the combination of a small diameter probe with a noncatalytic surface gives $D_5 < 10^{-3}$, or, effectively, $\phi \approx 0$. A large catalytic model gives $D_5 > 10$, or, effectively, $\phi \approx 1$. This illustrates the range of conditions possible with

the present facility. Many references quote values of k_w near 10^3 cm/sec for many engineering materials, so that with intermediate-sized probes it is not unreasonable to at times expect values of ϕ in the 0.50 range.

The above example, used in conjunction with Figure 10 for values of (h_d/h_o) up to 0.70, serves to point up the wide range of heat transfer variations to be expected. As mentioned in Section III, it is often advantageous to operate under limiting conditions with $\phi = 0$ or 1. However, one is seldom completely assured of this condition, since k_w values reported for a single material vary over a range of three orders of magnitude, depending on the facility and test techniques employed. There appears to be a need for development of a "self calibrating" probe technique along the lines of that discussed in Ref. 31 that can, in fact, be used independently of k_w values determined elsewhere. Reference 32 presents an experimental study wherein the surface properties of arc tunnel probes were calibrated independently in a glow discharge shock tube facility of known dissociation level before and after arc testing. This technique was found satisfactory for determining arc jet oxygen dissociation levels.

The importance of the parameters (h_d) and ϕ becomes increasingly clear when one is faced with the necessity of calibrating the stream for model heat flux and enthalpy level using a calorimeter of a catalytic efficiency different from that of the actual test model. This situation can become even more involved if it is desired to perform meaningful tests of an identical nature in several arc tunnels. In this case one faces the strong possibility that each tunnel may operate with a different atom concentration at the same heat flux to a common calorimeter. Different heat transfer rates then appear during final tests in each tunnel because models with different effective catalytic efficiencies (ϕ) are operated.

VL CONCLUSIONS

It has been shown that, because of physical limitations, arc tunnels are often required to operate with nonequilibrium flows. Unlike equilibrium flow, for which chemical states in the flow are uniquely determined by local thermodynamic parameters, nonequilibrium flow necessitates monitoring the chemical states throughout the entire system. The monitoring is facilitated by the use of Damköhler numbers, in terms of which limiting flow regimes can be defined. In the frozen limits, flow quantities are again well defined. Interpretation of test results obtained therein is therefore simplified.

In surface heat transfer measurements made in a frozen nozzle flow, both the frozen dissociation level and the surface effective catalycity are important factors whose effects on heat transfer has been demonstrated by sample calculations based on the operating condition of the arc facilities of this laboratory. Reliable values of these parameters are therefore essential for meaningful interpretation of the measured heat transfer, especially when measurements are made in different facilities.

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13 ABSTRACT The important features of nonequilibrium flow typical of an arc tunnel flow system are outlined. An arc heated flow system is analyzed in terms of its subsystems and corresponding local flow Damköhler numbers. Operating ranges characterized by equilibrium and frozen flow limits are specified. The effects of nonequilibrium flow on test results for a range of possible operating conditions is discussed.		

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